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Lubrication

A Technical Publication Devoted to the Selection and Use of Lubricants

THIS ISSUE

Engine Wear

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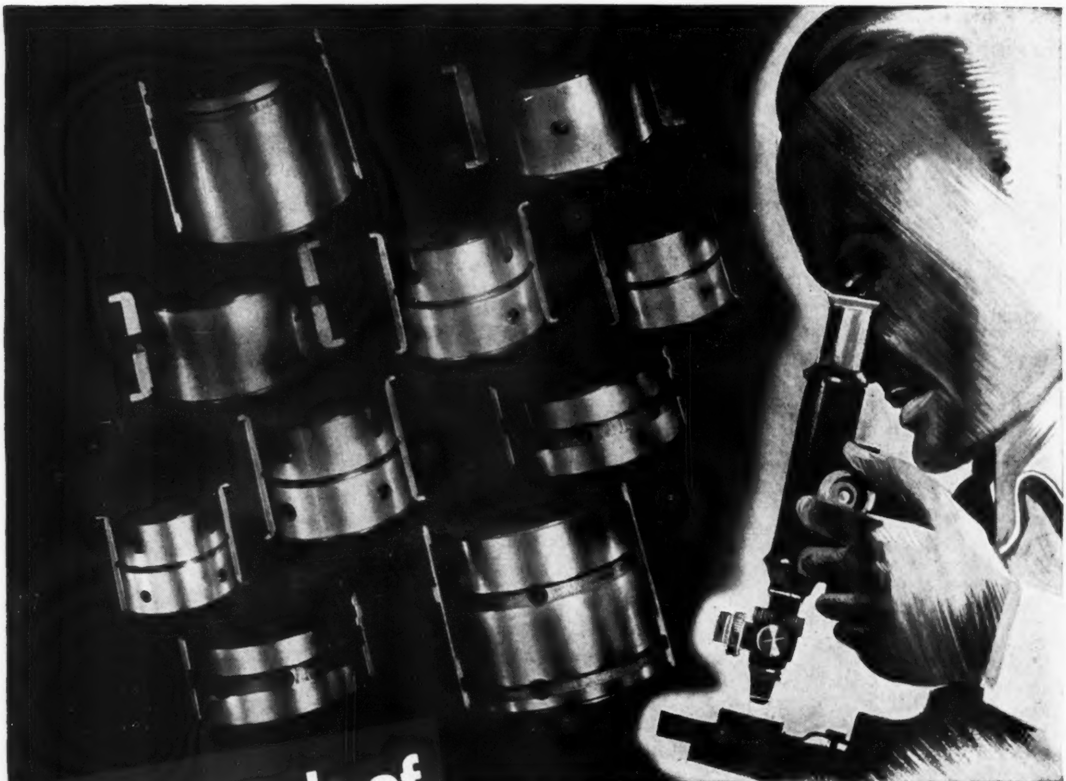

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Engine Wear

Engine wear occurring under high temperature conditions as differentiated from "corrosion wear," or wear occurring under cold running conditions, has been the subject of extensive investigation for many years. This article endeavors to summarize briefly the mechanism by which high temperature wear occurs. Perhaps some will disagree with the theories herein advanced, but it matters not, so long as these theories set others to thinking and working so that the problem of wear, particularly cylinder wear, will not limit the power output of engines of the future.

A STUDY of the wear of high speed engines may justifiably separate their life history into two distinct phases,—

1st. The "wearing-in" period, which prepares the working surfaces for their useful life, and

2nd. The "wearing-out" period, which occurs throughout their useful life.

The *wearing-in period* is indispensable and is usually carried out at least in part by all engine builders. Aircraft engine builders carry it to completion because these engines must pass rated power tests before leaving the factory, and this is not possible until wearing-in has been completed. This procedure is necessary because even the best manufacturing practice today cannot make such parts as piston rings and cylinders to fit each other well enough to operate under rated power at once.

There are two important reasons for this: One involves the actual nature of the contact between mating surfaces; it will be discussed later. The other is that cylinders of internal combustion engines when developing power, do not maintain the shape and dimensions given in the shop.

Change of shape and size is due to thermal and mechanical distortion, both of which are too variable in operation to be more than approximately compensated for in design. The cylinders may expand in diameter at the top more than at the bottom, thus becoming tapered—some small area may bulge from the strains of hold-down bolts or uneven heating, etc. The only way cylinders and piston rings can be brought to a condition suitable for operating at the high powers at which engines are now rated, is to wear them in while developing power. This is a time-consuming operation for an engine builder, and one which warrants careful study to see what can be done to reduce it.

The *wearing-out period* is contingent upon a variety of combinations of operating conditions. Just when it may start will depend upon the engine itself, the features of design and the care it is given as to maintenance. Some of the most usual conditions which may affect engine cylinder wear involve:

1. Absence of lubrication when starting up.
2. Water condensed on the cylinder walls.
3. Oil contamination due to ineffectual (or lack of) air cleaners.
4. Ineffectual oil cleaning due to clogged oil cleaners.

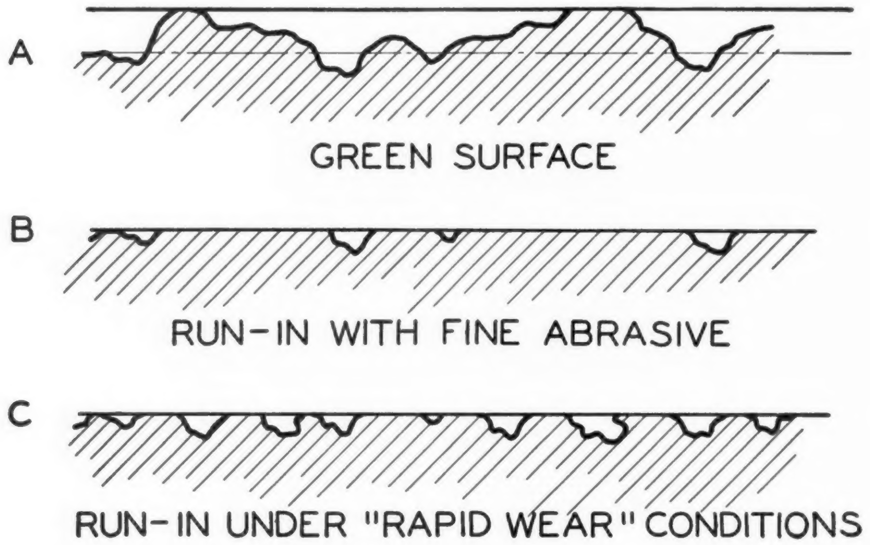

Fig. 1—Assumed appearance of magnified sections of metallic surfaces.

5. The metallurgical and micro-structural nature of the materials in contact.
6. Surface finish.

SURFACE CONDITION

As the condition of the contact surface is a basic factor it is well to start with a study of the probable microsurfaces of newly machined parts, such as piston rings and cylinders which are typical of all rubbing surfaces not completely separated by a dynamic oil film and are probably the most critical parts of the engine, at least during the running-in process. There is ample evidence that a highly magnified section of even the best newly machined surface may look like Figure 1, where for convenience the vertical scale, representing about 10 to 100 micro-inches*, is magnified much more than the horizontal scale. These jagged peaks are parts of wavy ridges left by all turning, grinding, lapping and similar operations, even though so slight as to appear smooth to the unaided eye. Contact with another surface would be along the tips of the peaks or ridges; it is clear that the total area of actual contact would be only a small fraction of that intended.

Such a condition has been demonstrated by measurements of the electrical resistance between such surfaces. Bowden and Tabor** have shown that with optically flat steel surfaces:

1. The area of actual contact is dependent only on the total load and is independent of either the nominal area or of the degree of surface finish.
2. Contact exists at only a very small fraction of the nominal area.

Thus for a load of 660 lbs. between test blocks having a nominal area of about 3¼ sq. in., the total of all the myriads of small contact areas was less than 3/100 sq. in. When this same load was applied to similar surfaces having a nominal area of but ⅛ sq. in., the actual contact area was practically the same. As the load was reduced, this net contact area diminished by approximately the 3/2 power, being only 0.0003 sq. in. at 44 lbs., which corresponds to a unit load of more than 130,000 lbs. per sq. in. at the actual contact area.

It may easily be expected that when such surfaces are rubbed together, the highest peaks will be removed, then lower and lower peaks, until the load is carried by a much larger number of smaller peaks, such as at B-B (Figure 1). Thus the important differences between "green" surfaces as machined, and as "run-in," is that in the latter case the contact area is divided between a much larger number of smaller areas. Probably in the ideal case all contact areas would be about equal in size, and equally spaced.

* Millionths of an inch.

** Proceedings Royal Society of London, vol. 169, page 403. From "Area of Contact between Stationary and Moving Surfaces," by F. P. Bowden and D. Tabor.

HEAT A FACTOR

While evidence indicates that the total contact area is not appreciably altered by the running-in process, there are important reasons why such a run-in surface is necessary. One must bear in mind when contemplating this probable surface, that the friction resulting from rubbing such surfaces together creates heat *at the points of contact*, and that the temperature at these points must rise to such a level as is necessary to supply the temperature gradient which will carry the heat of friction to the body of the metal.

While the total heat of friction may not be great enough to raise appreciably the temperatures of the masses of the metals whose surfaces are in contact, so much heat is generated at such small portions of these surfaces that unexpectedly high local temperatures may exist at those areas. The situation has been well expressed by comparing it to the striking of a match, where the high temperature necessary to ignite the match results from a very small quantity of heat. Many other such examples are familiar to most of us; consider the sparks thrown from emery wheels, or occasionally from the brake shoes of railway cars. In such instances we have visible evidence of very high local temperatures being developed without any great rise in the temperature of the body of the rubbing material.

Actual measurements* of the temperature between rubbing surfaces have been made by means of the voltage generated when using the rubbing contact between dissimilar metals, as a thermocouple. Temperatures above 1800 degrees Fahr. were measured between steel and Constantan at a velocity of 36 ft. per second and a load of only 0.22 lbs. (180 lbs./sq. in.). Such temperatures vary directly with the rubbing velocity and friction (= load × coefficient of friction), and inversely with the thermal conductivities of the metals. Apparently they are limited only by the melting temperature of one of the rubbing materials.

Mathematical analysis** indicates that the local temperatures at the areas of contact rise as such areas slide past each other, so that the part of these areas near the trailing edges reach the highest temperatures. This is another way of stating that the highest temperature reached by any contact area is dependent on its size, all other factors being constant. When contact is divided among a larger number of smaller areas, these temperatures are reduced.

* Proceedings Royal Society of London, vol. 154, page 640 "Physical Properties of Surfaces," by F. P. Bowden and K. E. W. Ridler.

** "Theoretical Study of Temperature Rise at Surfaces of Actual Contact under Oiliness Lubricating Conditions," by H. Blok. Inst. Mech. Engrs. Proc. Genl. Discussion on Lubrication and Lubricants—Oct. 1937—page 222.

THE "WEARING-IN" PERIOD

During the period of "wearing-in" of two companion metallic surfaces, they may pass through "burnishing" or "scuffing" stages. Excessive "scuffing" borders on the "wearing-out" period when "scoring" or "galling" may

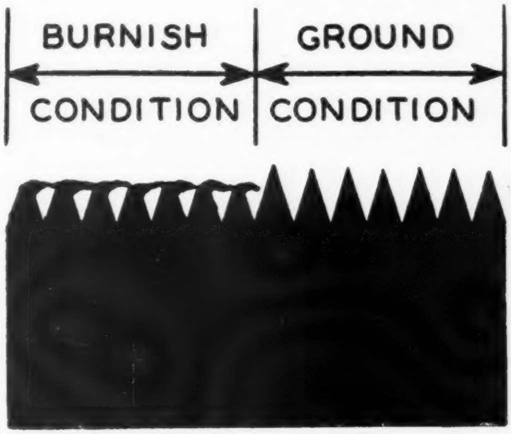

Fig. 2—Comparison of a burnished vs. a ground surface condition, showing how in burnishing the peaks are ironed over, so to speak, whereas the peaks on a ground surface remain as such, to carry the expected load. Note that in this example the surface irregularities are not removed but displaced.

occur. Before discussing these manifestations of surface failure, it is well to adopt, at least tentatively, some definitions for the terms ordinarily used, especially as there is a wide difference in the definitions for "scoring," "galling," etc., used by certain authorities. Since there seems to be no general agreement, the reader is requested, while reading this article, to accept the definitions we indicate for the purpose in view, i.e.,

"Burnishing" is a smoothening process akin to polishing.

"Scuffing" is considered as a general term covering all manifestations of locally welded metal, even the slightest surface scratches from this cause.

"Scoring" is the next step, and finally "galling" which occurs just before seizure.

It is probable that as two new or "green" surfaces are *slowly* rubbed together, the peaks or local high spots which take the brunt of the load, will be chipped off if brittle, or deformed if plastic. If the former, metal will be lost by the surface, but if the latter, it will not. This is another way of stating that wear will occur in one case and not in the other. In either case the highest and largest areas will be eliminated so that an increased number of smaller areas will carry the load. Eventually, the load is distributed so that further rubbing will result in no further reduction in the size nor increase in the number of points of contact; the surfaces

may then be considered as "worn-in" for the particular speed and load which were used.

Burnishing

When the surface temperature is then raised a little higher, as by increasing the load or speed, or the temperature of the cylinder, this cycle may be repeated. But when it is increased far enough, many of the surface peaks will become plastic and flow. This involves the phenomenon of "burnishing," which by ironing out all peaks, increases the smoothness of the softer surface. At first thought this might appear to be desirable, but experience has proven that the ideal surface for carrying high loads, while flat, is not perfectly smooth, but consists of a large number of mounds of more or less equal heights. See Fig. 2.

Surface "Fuzz"

During the wearing-in process it is necessary also to remove from a newly machined surface the thin layer of metal which has been heated and stressed to the fatigue point by the machining operations, because it does not possess the physical characteristics of the body of the metal. This layer has properties similar to those which probably prevail in the chips removed by cutting tools, where the work of cutting has either caused the generation of sufficient heat to result in plastic flow of the metal, with the resultant loss of the desired physical structure, or where shear between adjacent crystals has exceeded the fatigue strength of the metal and left it weak. Because of the inferior properties of this surface, its resistance to wear is probably lower than expected from the known properties of the parent metal; so "initial wear" which occurs while this layer is worn off takes place much faster than afterward.

Surface "fuzz" has been a term applied to the condition of the surface metal after most machine operations. One seldom stops to think how severe the metal surface is stressed during the usual machining operations. For instance, according to Wallace*, ordinary finish grinding subjects the metal to pressures in the order of 2,000 to 20,000 pounds per linear inch of contact at speeds of 6,000 to 10,000 ft./minute. Even in honing operations pressures are developed in the order of 500 to 1,000 lbs./sq. in., which is sufficient in some cases to cause distortion of the metal at the surface which is being finished. In contrast (according to the same authorities), the intensity of work done in "super finish" is limited to pressures not greater than 3 to 50 pounds per square inch, at speeds of not more than 3 to 50 feet per minute.

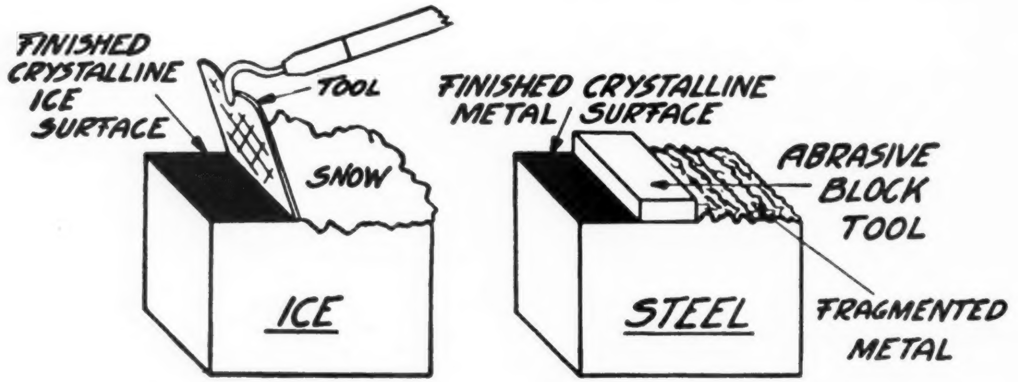

Fig. 3—Removal of surface "Fuzz" can be likened to removal of snow from ice. A machined steel surface will have a layer of fragmented material lying thereon in much the same manner as snow lies on ice, according to D. A. Wallace on "The Preparation of Smooth Surfaces," discussed at the Special Summer Conferences on "Friction and Surface Finish" held at the Mass. Inst. of Tech. June 5-7, 1940.

Scuffing

When the surface temperature is increased above the burnishing temperature, the trailing edges of the largest contact areas will reach temperatures high enough to weld, and they will therefore be torn out of the weaker surface material. This metal, which will then project momentarily across the line of sliding contact between the surfaces, may be sheared off by the next high spot to pass, and left in the adjacent valley.

Since the contact areas of "green" surfaces are very uneven in size, it is quite possible for the running-in process to be carried to a point where welding will stop, because the disintegration of the largest areas will have proceeded until none are left which are large enough to develop welding temperatures. This is what is meant by self-healing wear. But if the load

* Proceedings of the Special Summer Conferences on "Friction and Surface Finish," held at Massachusetts Institute of Technology, June 5, 6 and 7, 1940, page 30.

or speed has been increased too rapidly in the running-in process, such large areas may have welded, that the metal torn out would be larger than the following high spots. Then instead of shearing off the welded metal, the following high spot would be sheared off by the welded metal, or might even weld to it, and thus increase its size still further.

Scoring or Galling

The process might then become regenerative, more and more metal being picked up until the familiar smeared metal, characteristic of "scoring" or "galling" becomes visible; the changed dimensions of the parent metal ultimately would cause seizing. The same result would occur if the welded metal instead of being sheared off, were plastically flowed over the harder surface, when it is too smooth to provide valleys of such size that it could be worked into them, and thus be gotten out of the way. This would be another reason for the fact that surfaces, especially the harder of a rubbing pair, can be too smooth to carry high loads.

Now consider that the gradual running-in which caused the progressive disintegration of the largest contact areas, has been carried on until it has become self-healing, and welding has ceased. Under these conditions moderate increase in speed or load will again cause welding and disintegration of the largest remaining contact areas, and promote another self-healing condition. Continued increments of load or speed will result in repetitions of this self-healing condition, with probably more and more areas welding simultaneously until all contact areas are substantially equal.

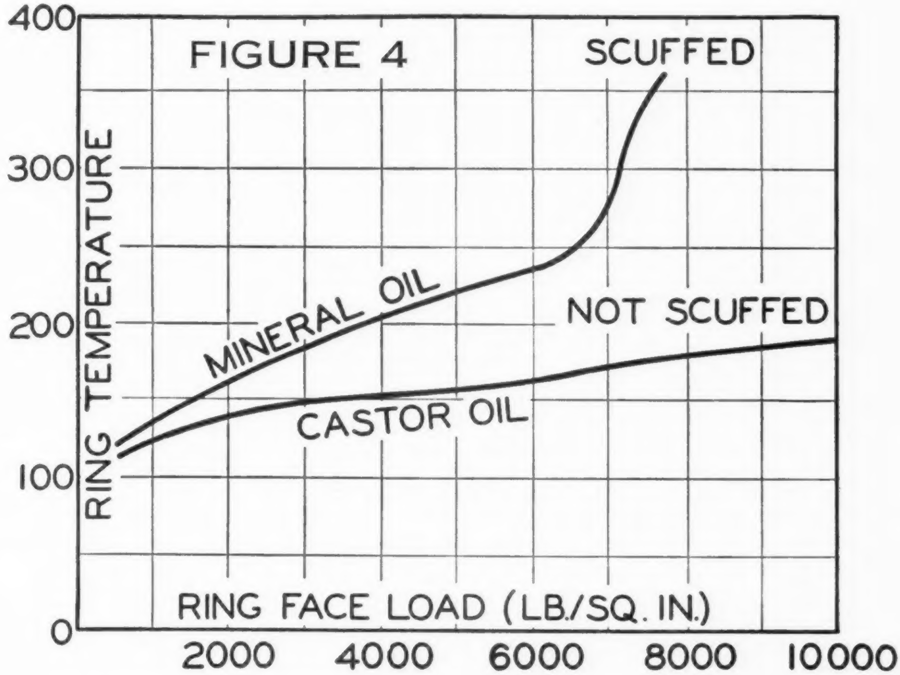

Fig. 4—Showing comparative curves for castor oil and a straight mineral aircraft engine oil, plotting ring face load against ring temperature.

Rapid Wear

Any further increment of speed or load can then no longer be self-healing, because any or all contact areas may weld, and when they tear out they leave a new surface with new hills and valleys which are no smaller. This is what is known as *rapid wear*; it must not be confused with the type of wear which results from the presence of unwanted abrasives, such as sand or dust, which inadvertently get between rubbing surfaces.

It is advisable to add a word of caution about confusing scratches on piston rings from sand or other grit which may be on surfaces when assembled, with the early stages of scuffing. Scratches from both causes often look very much alike, but their means of prevention are very different, viz., the use of oil filters for the removal of dust and other similar abrasive material.

Care and cleanliness during assembly will aid materially in reducing the possibility of

initial scoring. "Assembly dirt" usually does its damage before the oil filter has a chance to remove it.

Thus it may be seen that the three phenomena of scoring, self-healing scuffing, and rapid wear, are all manifestations of the welding of local high spots, and differ from one another only by being regenerative, self-healing or stable.

PREVENTION OF WELDING

Having reviewed the surface conditions which may affect the general subject of scuffing, it is in order now to consider the various means of preventing or at least reducing welding which is the basis of any manifestation of scuffing.

Any factor affecting the temperature of the contact areas will affect scuffing. The importance of minimizing the size of individual areas of contact by running-in has already been discussed.

Friction is of course one of these factors and the only one which may be influenced by the lubricant. An "oily oil," such as castor oil, appears to produce so much lower frictional heat than straight mineral oils of corresponding viscosity, that it may eliminate serious scuffing simply by holding the maximum surface temperatures below the welding points.

By the term "oiliness" we mean that quality of a lubricant (aside from its viscosity) which affects the friction between two surfaces *in contact* when moving with respect to each other. This property has been defined in other words by Claypoole* who suggests that: "Oiliness is the result of interaction of molecular and surface forces at the interface. The maximum effect of oiliness is reached only when the contacting surfaces are separated by an oil film of molecular dimensions. There is no oiliness effect in fluid film lubrication."

There are many additives which give "oily" qualities to lubricants, but the usual test methods for the evaluation of friction coefficients are not suitable to predict their performance in engine cylinders as they do not permit of sufficiently high speeds or loads.

One of the most promising devices available for an indirect study of friction is the scuffing machine developed by The Perfect Circle Company. In this machine, a segment of a cylinder is reciprocated under a segment of a piston ring. A curve is drawn between the load applied to the ring segment and its tempera-

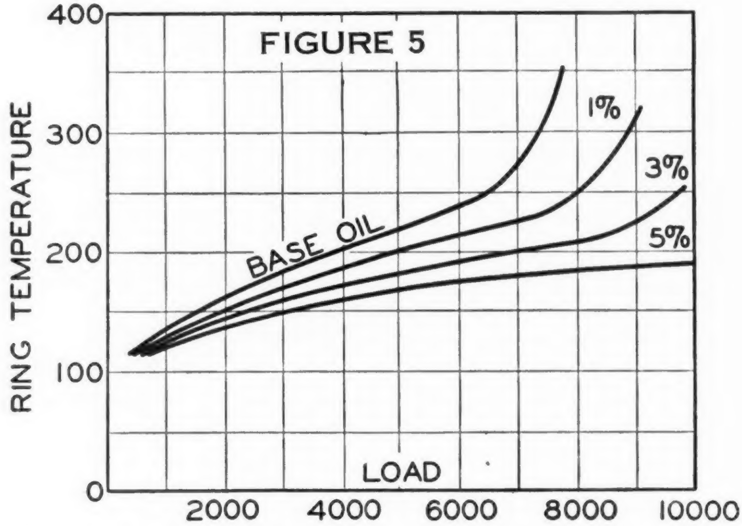

Fig. 5—Showing the results which may be expected from addition of an "oiliness" agent to the straight mineral oil referred to in Fig. 4. Note the complete absence of scuffing.

ture is measured by an imbedded thermocouple, though it is realized that the actual surface temperatures are considerably higher than indicated by the thermocouple. Each point denotes the equilibrium temperature reached after application of the corresponding load. When a load is reached where the temperature fails to level off at an equilibrium value and continues upward, failure or scuffing is indicated. Figure 4 shows comparative curves for castor oil and aircraft engine oil. Note that with the former, there is hardly half the temperature rise, and that no scuffing developed with it up to the limiting load of the testing machine. Figure 5 indicates the result which might be expected by addition of an oiliness agent such as one of the fatty acids.

E. P. MATERIALS

Physicists tell us that metals would not have to be heated to weld if their surfaces were *perfectly clean**. However, when a fresh surface is exposed by breakage or cleavage of metal it almost instantly absorbs or combines with enough oxygen or other gases from the air, to prevent it from adhering to a similar surface.

* Quoted by G. B. Karelitz, page 102, "Proceedings of the Special Summer Conferences of Friction and Surface Finish." Massachusetts Institute of Technology, Cambridge, Mass., June 5, 6 and 7, 1940.

* "The Nature of Static Friction" by Walter Claypoole and L. W. Cook. Journal Franklin Institute, vol. 233, May 1942, page 453.

Metal ordinarily considered clean is almost always covered by a very tenacious oil film which is very difficult to remove. Accordingly, metals must be heated to be welded, and must be reasonably clean. Heat drives off the oil film and adsorbed gases, while "flux" aids in carrying away oxides and other such films. Obviously satisfactory performance of the rubbing surfaces in any engine or machine requires that the tendency to weld be reduced to a minimum; therefore, surface contaminants are definitely desired.

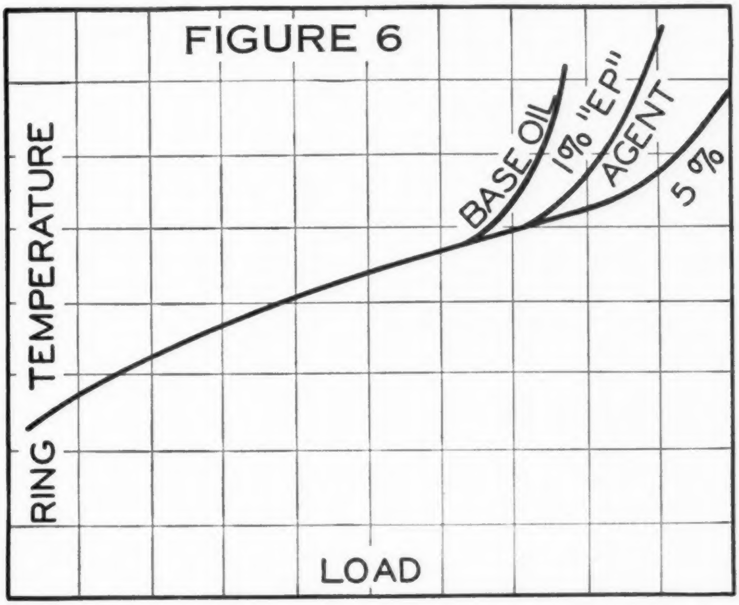

Fig. 6—Showing the probable effect of increasing additions of an E. P. agent to the straight mineral base oil referred to in Figures 4 and 5.

Lubrication promotes an oily surface condition which is ample to prevent welding until the contact peaks exceed temperatures high enough to evaporate the protective oil film. Even then oxide coatings are still present which carry the protection to still higher temperatures. But these are ordinarily very thin, and become appreciably effective only when augmented by deliberate chemical treatment. Other compounds with iron*, such as sulphates, etc., and phosphates particularly are effective, and may be formed readily by chemical treatment.

Function of the Additive

One of the innovations in lubrication introduced during the last decade, has been the addition of chemical compounds which give the so-called "E. P." (Extreme Pressure) quality. These compounds do not, or should not, react with the metals in an engine at any normal operating temperature, because this is a form of corrosion, which may remove some of the metal. It is preferable to seizure or rapid wear under high power output, but when and where it is not needed for this purpose, it is of no advantage and should not be permitted. However, when any part, such as a local surface peak, approaches the temperature range which is necessary for welding, the chemical additive combines with that part, and forms a surface contaminant which greatly retards welding.

Welding can be almost eliminated by these compounds. Some of them, such as the sulfides, when raised to temperatures of incipient welding, develop surface compounds which easily "chalk" off, and by removal of the combined metal cause measurable wear. Others, such as the phosphides, may develop, under similar conditions, hard tenacious films which are more resistant to wear than the bare metal. All such additives tend to reduce welding or scuffing simply by acting as surface contaminants, and apparently do not function by reducing the heat generated by friction.*

Figure 6 indicates the probable effect of increasing additions of an E. P. agent in an oil. This should be compared to Figure 5. It should not be forgotten that as some E. P. materials may have some oiliness properties of their own, their curves in turn would be intermediate to Figures 5 and 6.

The "feathering" of piston rings, on the other hand, which results from temperatures which cause excessive metal flow, cannot be expected to be reduced solely by E. P. properties of an oil. If this is so, increased oiliness becomes the only property of a lubricant which will reduce "feathering."

How Straight Mineral Oils React

Since oil acts as a surface contaminant until it is driven off by heat, straight mineral oils, containing no E. P. additive, will probably

* "Piston-Ring Coatings and Their Effect on Ring and Bore Wear," by Max M. Roensch. SAE Trans. 1940, page 221. Presented at the World Automotive Engineering Congress of the S.A.E., San Francisco, Calif., June 8, 1939.

* "The Influence of Surface Films on the Dry and Lubricated Sliding of Metals," by T. P. Hughes and G. Whitingham. Trans. of the Faraday Society, Vol. XXXVIII, Part I. Jan. 1942, page 9.

differ from each other in their ability to prevent scuffing, inversely in the order of their volatility. When E. P. agents are present, however, this characteristic has very little more effect than to determine at what temperature the transition occurs from the protection afforded by the oil, to the contaminant resulting from the E. P. agent. It is probable that there is no other significant characteristic of a straight uncompounded mineral oil which may affect scuffing except perhaps viscosity rise under pressure; as yet, however, corroborating data is lacking.

In summation, attention should again be drawn to the role of the lubricant in acting as a surface contaminant. Occasionally "green" engines scuff simply because the oil supply is not adequate, due to tight bearing clearances and the high degree of effectiveness of new oil scraper rings. The performance of any oil in checking scuffing is never so evident as when it is inadvertently absent. Many a "green" engine has been carried over its break-in period by adding some oil to the gasoline, so that lubricant reaches the piston rings directly, from the top.

THERMAL CONDUCTIVITY

Another factor which controls the temperature of the contact areas is the thermal conductivity of the metals in contact. The higher the conductivity, the lower the temperature gradient between the point of heat generation, and the mass of the metal, for the conduction of a given amount of heat.

Cylinder metals may vary considerably due to the effect of nickel and other similar elements in their alloys. For example, one grade of steel used for aircraft cylinders has a conductivity which decreases with increase in temperature, being 15 per cent less at 600 degrees Fahr., than at 200 degrees Fahr. There are indications that it may decrease considerably more as higher temperatures are approached.

On the other hand, another widely used steel shows increasing conductivity with increasing temperature, though the conductivity is only about 70 per cent as great as the former at 200 degrees Fahr., but it is not much less at 600 degrees Fahr., and may even be higher at welding temperatures. Very little information is available on the thermal conductivities of such alloy steels at elevated temperatures, but since some steels obviously scuff more readily than others, this might well be considered in specifying the steel for cylinder barrels.

Cylinder Temperature

Cylinder temperature also affects the temperatures of the contact areas. Temperatures caused by friction are of course implied as being above the normal temperature for the parent metal. Thus, any change in cylinder temperature, as may result from various degrees of cooling, will have a corresponding influence on the temperatures of the contact areas. This is emphasized by the difficulty of cooling aircraft engines at very high altitudes, for any increase in cylinder temperature will increase the tendency to scuff or rapid-wear, unless some compensating reduction is made in power output.

CONCLUSION

Contact between metal surfaces which rub together, without definite separation due to a dynamic oil wedge, such as piston rings and cylinders, occurs at a myriad of very small areas, relatively widely spaced. The total of all these areas is but a very small fraction of the nominal area where contact is intended, and is controlled by the nature of the metals and the applied load. It is not affected by the nominal area, the unit loading, nor the nature of the surface finish.

When such surfaces are rubbed together, the frictional heat generated causes extraordinary temperatures to exist in these contact areas, these temperatures being proportional to the contact areas. One important function of the running-in process is to equalize these areas, by a progressive disintegration of the largest, thus reducing the maximum temperatures which will occur at these areas for any given operating conditions.

This disintegration is accomplished by *controlled* welding and tearing away of metal which is subsequently sheared off into the micro-valleys existing between the contact areas. See Figure 1. This is of course accompanied by a rapid wearing away of unwanted metal and may be aided by the use of anti-weld additives which produce surface compounds which "chalk-off" readily.

After the surfaces have been properly prepared by running-in, further wear may be prevented even at very high engine outputs, by any or all of the following:

1. Reduction of frictional heat, by use of a sufficiently "oily" lubricant.
2. Use of an oil with a high evaporation temperature.
3. Use of an oil containing anti-weld agents, which provide a hard tenacious coating.
4. Use of metals of the highest practical thermal conductivity, and a design incorporating the shortest possible thermal paths.
5. Use of the lowest cylinder temperature practical, giving due regard to power required for cooling.

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